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A study of semiconductor quantum structures by microwave modulated photoluminescence

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Abstract. Mixed types I-type II multiple quantum wells structures consist of alternating narrow- and wide GaAs wells (WW and NW), separated by AlAs barriers. Transfer of electrons from the narrow- to the wide well results in the formation of two-dimensional electron and hole gases (2DEG and 2DHG) at the WW and NW, respectively. The present study investigated the influence of the 2DEG and the 2DHG on the optical properties of the materials. The study utilized two modulations techniques: double beam photoluminescence and microwave modulated PL, offering high-resolution spectroscopy, control of the density of the gases and their kinetic energy. The results showed that the existence of the low density 2DEG in the wide well cause the formation of trions or plasma-like recombination. In addition, electrons transfer through the barrier leads to a barrier-NW indirect recombination emission. The latter is influenced by an electrostatic potential induced by the two-dimensional gases.

1. Introduction

The optical properties of quantum well (QW) structures, containing a two-dimensional electron and hole gases (2DEG and 2DHG), have a scientific and technological importance [1, 2]. The influence of those gases are studied in mixed type I-type II quantum wells (MTQW) structure, enabling the control of the electron-density (n_e) between 10^{10} – 10^{11} carriers/cm² by optical pumping [4–7].

The present study utilized MTQW's structure that is drawn schematically in Fig. 1(a). This structure consists of a sequence of alternating narrow- and wide GaAs wells, separated by AlAs barriers [1]. Furthermore, it is designed in such a way that the lowest Γ state of the GaAs narrow well (NW) is higher in energy than the lowest X state of the adjacent AlAs layer, leading to type II alignment. However, the last X state is energetically higher than the Γ state of the wide GaAs well (WW), creating type I alignment. Then, photocreated electron–hole pairs become spatially separated by a rapid (~30 ps). Γ – X – Γ electron transfer from the NW to the WW. Conversely, the hole tunneling through the barrier occurs in the millisecond range, thus leading to a temporary accumulation of the 2DEG in the WW. The present study describes our attempts to follow the interactions of the 2DEG and 2DHG with other photogenerated species. The results revealed the existence of the following events: (a) attachment of an excess electron to an existing exciton in the WW, to form a negatively charged specie, named a trion [4, 5]; (b) direct recombination of an ensemble of free electrons with an existing hole within the WW, forming a plasma-like emission band [5, 7]; (c) indirect recombination between electron in the barrier X state and the 2DHG in the NW. The present study utilized double beam photoluminescence (PL) and microwave modulated PL (MMPL) for the study of the aforementioned processes.

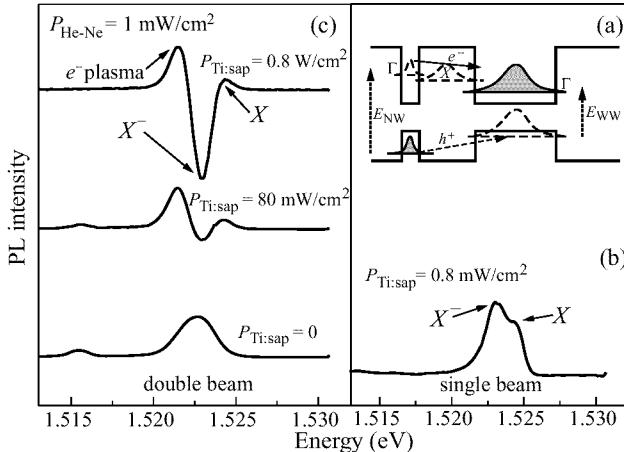


Fig. 1. Schematic energy band diagram of MTQW structure (a), PL spectrum under Ti: sapphire laser excitation (b), and PL spectra under double beam excitation with modulation of the He-Ne laser (c).

2. Experiment

A MTQW structure, consisting of 30 periods of alternating, wide (198 Å) and narrow (26 Å) GaAs wells, separated by 102 Å width AlAs barriers, have been used in the present research. The sample was placed in a microwave (mw) resonance cavity (operating at 10.755 GHz), which by itself was mounted in the liquid-He dewar with a superconductive magnet (up to 3 T). The mw power dissipation within the cavity at 0-dB attenuation was about 55 mW, however only 2% of it was absorbed by the sample.

The electron–hole pairs in the NW were generated by nearly resonance excitation with $E_{L1} = 1.96$ eV, by a He–Ne laser. The excitons in the WW were generated by nearly resonance excitation with E_{WW} , by a Ti sapphire (1.62 eV) laser. Accumulation of electrons in the barrier was formed by excitation with an Ar^+ (2.41 eV) laser. The single beam, double beam and mw modulated PL spectra, were all recorded at 1.4 K. In addition, in the double beam experiment, both lasers impinged on the same spot of the sample.

3. Results and discussion

A representative PL spectrum of the MTQW structure, excited at $E_{L1} = 1.96$ eV, is shown in Fig. 1(b). It consists of exciton (X) and trion (X^-) bands, centered at 1.524 eV and separated by 1.7 meV. A PL spectrum of the MTQW structure, excited at E_{NW} , is shown in Fig. 1(c) (bottom curve). It is dominated by a broad and featureless band, associated with the recombination between large density of 2DEG (generated with E_{NW}) and holes in the WW. It should be noted that this plasma-like band extends to lower energy than the corresponding exciton and trion, due to the re-normalization of the conduction band, occurring at large n_e [7]. The weak band at 1.515 eV corresponds to a bulk GaAs substrate and will not be discussed any further.

The double beam PL spectra, recorded at two different excitation powers ($E_{L1} = 1.96$ eV and $E_{L2} = 1.62$ eV) are shown in the middle and top curves of Fig. 1(c). It is seen that a modulation of n_e leads to difference spectra resolving the exciton (high energy and positive), trion (negative) and distinct plasma (low energy and positive) bands. The quenching of the trions population corresponds to their dissociation under intense flux of n_e and their conversion into excitons and plasma species [7].

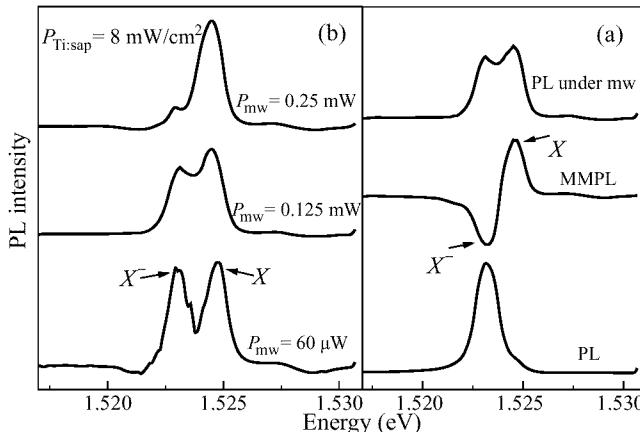


Fig. 2. The MMPL spectrum evolution as indicated in the text (a), PL spectra excited by Ti: sapphire laser under mw radiation at different mw powers (b).

The evolution of a MMPL spectrum is shown in Fig. 2(a). The bottom curve corresponds to a conventional PL spectrum, excited at E_{WW} with 8 mW/cm^2 . A trion band dominates it, while the exciton emission is hardly resolved at this excitation power. The PL spectrum recorded under the influence of a mw radiation is shown at the top curve of Fig. 2(a), while the difference spectrum, labeled as MMPL, is shown in the middle curve. One can see that mw absorption causes a decrease of X^- with simultaneous increase of the X band. This is due to the induced collisions between mw-heated 2DEG with the trions that consequently lead to the dissociation of X^- . An absorption of $60 \mu\text{W}$ of mw power by the sample, still equalize population of excitons and trions in the WW (Fig. 2(b), bottom curve), however above this power, most of the trions dissociated and thus, the spectrum is dominated by the X band (middle and top curve in Fig. 2(b)). It should be noted that n_e is relatively small under E_{WW} excitation and therefore, the plasma band is not pronounced under the MMPL experimental conditions.

As indicated at the introduction, the electron transfer via the $\Gamma - X - \Gamma$ cascade of states results in a pause of 30 ps at the barrier. At this time, electrons make indirect recombination with the 2DHG in the N. Representative PL spectra of those indirect transitions are shown in Fig. 3. The spectra contain two groups, each consists of two bands, as labeled in the figure.

Recording the indirect transitions at various laser excitation powers (Fig. 3(a)) or strength of an external magnetic field (Fig. 3(b)) showed a minor influence on group II and pronounced change of group I. Group II was assigned to recombination processes at interface defects and will not be discussed any further. While group I corresponds to the recombination between the barrier X_{xy} (centered 1.752 eV) and the X_z (centered at 1.756 eV) with the 2DHG in the NW. Figure 3 suggests a blue shift of the X state-NW transitions and increase in their intensity with an increase in the laser or magnetic field strength. Our calculations [8] show that the blue shift is associated with an electrostatic potential induced by the 2DHG and 2DEG on both sides of the barrier. The latter leads to a blue shift of the X_{xy} and the X_z states (when the X_{xy} state exhibit a larger shift due to a smaller effective mass).

The MMPL spectra of the indirect transitions are shown in Fig. 4(a). Quenching of the entire spectrum suggests enhancement of the barrier electrons into the WW and reduction of their lifetime at the barrier, thus reducing the probability of recombination with the 2DHG

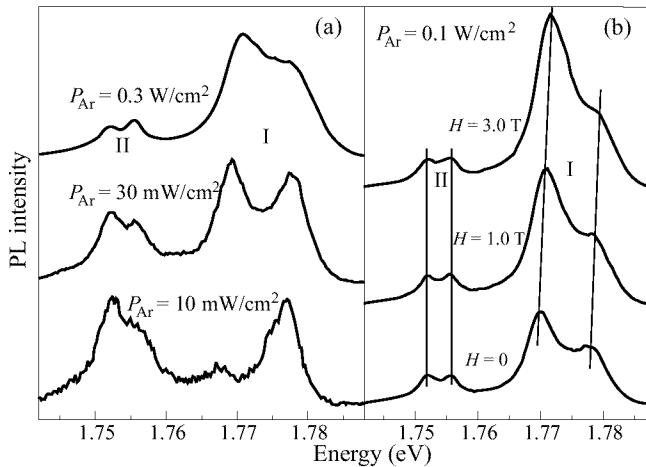


Fig. 3. PL spectra at the barrier energy range at different levels of Ar⁺ laser excitation (a), and different magnetic fields (b)

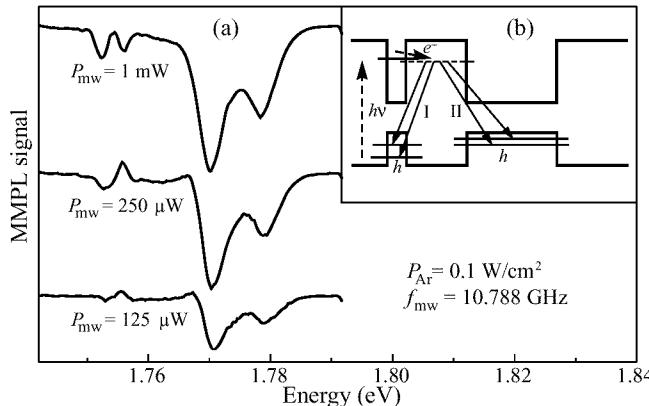


Fig. 4. MMPL spectra at the barrier energy range at different mw powers (a), recombination scheme, associated with the barrier (b).

in the NW, as shown schematically in Fig. 4(b).

Acknowledgements

The Project was supported by the Israel Ministry of Science and was conducted at the Technion Barbara and Norman Seiden Advanced Optoelectronics Research Center.

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